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14. ABSTRACT
This grant was redirected to focus on the search for high-Reynolds-number quiet flow in the Boeing/AFOSR Mach-6 Quiet Tunnel at Purdue. Quiet flow with freestream noise levels comparable to flight requires maintaining laminar nozzle-wall boundary layers; this becomes increasingly difficult, and increasingly useful, as the Reynolds number increases. After nearly five years of shakedown, quiet flow was finally achieved to a freestream unit Reynolds number of 2.8 million per foot, in early 2006. Although this is 90% of the prefabrication design value, it is achieved only intermittently. The maximum feasible quiet-flow Reynolds number remains to be determined, along with the conditions for achieving it reliably. Nevertheless, the facility is presently the only hypersonic quiet tunnel, anywhere in the world, and affordable operating costs have been maintained.

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Hypersonic Boundary-Layer Transition Research in the Boeing/AFOSR Mach-6 Quiet Tunnel

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1 Summary

This grant was redirected to focus on the search for high-Reynolds-number quiet flow in the Boeing/AFOSR Mach-6 Quiet Tunnel at Purdue. Quiet flow with freestream noise levels comparable to flight requires maintaining laminar nozzle-wall boundary layers; this becomes increasingly difficult, and increasingly useful, as the Reynolds number increases. After nearly five years of shakedown, quiet flow was finally achieved to a freestream unit Reynolds number of 2.8 million per foot, in early 2006. Although this is 90% of the prefabrication design value, it is achieved only intermittently. The maximum feasible quiet-flow Reynolds number remains to be determined, along with the conditions for achieving it reliably. Nevertheless, the facility is presently the only hypersonic quiet tunnel, anywhere in the world, and affordable operating costs have been maintained.

In addition, supplements to the core grant supported Purdue's portion of a joint effort to develop a Stability and Transition Analysis for Reentry (STAR). This effort is developing a mechanism-based transition-prediction tool for hypersonic applications such as the gliding reentry vehicles under development in the DARPA FALCON program. Purdue is contributing analysis of the existing experimental database, and is also making new measurements of nosetip roughness effects on windside-forward transition for blunt cones at angle of attack.

2   Introduction

In response to events, and feedback from the proposal referees and the program manager, the core research effort was redirected from quiet flow measurements on models to achieving high Reynolds number quiet flow in the nozzle test section. Supplemental experiments funded under STAR were focused on the study of nosetip roughness effects on frustum transition for blunt cones at angle of attack. The results are described in a series of AIAA Papers [1, 2, 3, 4, 5, 6, 7, 8, 9, 10]. Additional detail appears in three theses [11, 12, 13], two of which are archived in DTIC. Related efforts appear in Refs. [14, 15, 16, 17, 18]. Since considerable detail is readily available in these publications, the present final report was written as an overall summary.

3   Seeking Quiet Flow at High Reynolds Number in the Mach-6 Quiet Tunnel

3.1   Overview

Early transition of the boundary layer on the nozzle wall was identified as the cause of noise in the nozzle test section at high Reynolds numbers. Since many different factors can cause transition, and all must be controlled to maintain laminar flow, the problem is difficult. Hypersonic transition must be controlled on the nozzle wall, in order to develop quiet wind tunnels that permit scientific study of hypersonic transition on the test models, and neither flow is well understood. A systematic study of the possible causes was performed. From April 2001 through March 2005, many different possibilities were investigated, using the original electroformed nickel throat section. However, the tunnel remained quiet only below about 8 psia stagnation pressure, despite all these efforts; the key factor had not been identified.

Through these four long years, no changes were made to the electroformed nickel throat, since it had taken three years, great care, and roughly $50,000 to build, and there was great concern about damaging the mirror finish and the highly accurate contour. However, it became increasingly clear that some method of investigating the throat flow had to be found. Therefore, an aluminum surrogate throat was built, following a suggestion by Prof. Garry Brown of Princeton University. The surrogate was 3-4 times less expensive than the highly polished electroform, and could therefore be instrumented for surface pressure and skin friction measurements, although it was not expected to yield quiet flow at high Reynolds numbers, due to the limited surface finish that is possible with the soft aluminum. The surrogate was completed in January 2005 and first tested in March 2005. To our surprise, quiet flow has been achieved at increasingly higher Reynolds numbers, still using the low-cost surrogate throat.

The results of these studies are summarized below. Most of the null results were obtained using the electroformed nozzle. Recent results obtained with the surrogate nozzle are also presented, although most of these are preliminary, and serve to emphasize the limitations in our understanding of hypersonic boundary-layer transition and quiet flow tunnels. A complete description of the surrogate-throat results is to appear in Thomas Juliano's M.S. thesis, ca. August 2006.

3.2 Results Obtained with Electroformed Throat

Nine types of possible causes of the early transition were systematically investigated during 2001-2005, using the electroformed nozzle throat. On the basis of this research, they are organized below into two categories: Probable Causes and Other Possible Causes.

3.2.1 Probable Causes of Early Transition

3.2.1.1 Bleed Slot Separations Fluctuations can be generated at the nozzle throat due to unsteadiness in the bleed slot flow, probably due to separation bubbles in the main or slot flows [19]. It is well known that separation bubbles near the leading edge of an airfoil can cause early transition. Flat plates used for transition research are therefore installed with trailing edge flaps that allow controlling the location of the stagnation point, thereby eliminating the separation bubble on the working surface. A small leading-edge flaw in such a flat plate caused difficulties during the author's Ph.D. research [20]. Pauley et al. [21] performed a series of unsteady laminar incompressible Navier-Stokes simulations of a laminar boundary layer under the influence of an adverse pressure gradient. They observed that strong adverse pressure gradients caused periodic shedding from the separation. Such unsteadiness would likely cause early transition of the nozzle wall boundary layer. Also, the appearance of a steady separation bubble on the nozzle flow side of the bleed lip can adversely affect the stability properties of the boundary layer on the nozzle wall, leading to early transition [22]. Computations reported in Refs. [7] and [10] make this the most likely cause at present. This inference has drawn strong support from recent measurements with the surrogate throat, discussed below.

3.2.1.2 Noise Exiting the Driver Tube Fluctuations or nonuniformity in the driver tube flow could lead to early transition [6, 9]. Near the centerline, the contraction-entrance massflow fluctuations are mostly below the 1% criterion set by Beckwith [23]. However, the fluctuations increase to as much as 1.6% near the walls, and there is clear evidence of free-convection effects in the contraction. Since quiet flow has been achieved to 135 psia despite these flaws, they do not seem critical at present. Nonetheless, they will have an effect on the mean-flow uniformity and the residual fluctuations, if not on the nozzle-wall transition, and must remain an issue for further study [13].

3.2.2 Other Possible Causes of Early Transition

3.2.2.1 The Nozzle Shape The first concern was a fundamental problem with the use of a very long nozzle which is not captured by the e^N analysis. However, this now seems unlikely, since transition flashes forward along the whole downstream half of the nozzle at about the same pressure. Fig. 1 shows pitot measurements of the fluctuations on the centerline at different axial distances along the 102-inch nozzle [4, 3]. The RMS is normalized by the mean and plotted against the instantaneous driver tube pressure, as measured on the wall near the entrance to the contraction. At high pressures, the fluctuations are characteristic of turbulent nozzle-wall boundary layers. The noise rises with falling pressure as the boundary layer becomes intermittent, and then drops to levels suggestive of laminar boundary layers, as the signal-to-noise level becomes poor. The drop to laminar levels occurs at about 8 psia, for locations ranging from 45% to 85% of

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the nozzle length, suggesting a bypass of the conventional linear instability processes (assuming no separation bubble(s)). Fig. 2 shows that the same effect was still present in the surrogate nozzle when it transitioned at about 90 psia, in Oct. 2005. Here, both runs began at a driver-tube pressure of 120 psia and a driver-tube temperature of 160°C. Similar data was obtained in July 2005 when transition was occurring at 37 psia. Unlike in the NASA Langley experiments, transition has always been independent of axial location, to the extent measurable, clearly indicating a bypass of the usual instability phenomena, even with the surrogate throat.

Figure 1: RMS pitot pressure on nozzle centerline at various distances downstream of the *electroformed* throat
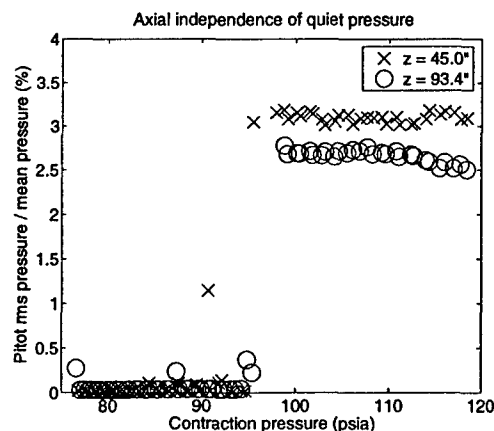

Figure 2: RMS pitot pressure on nozzle centerline at various distances downstream of the *surrogate* throat

3.2.2.2 Limits on the Downstream Nozzle Polish   The downstream portion of the nozzle was initially not polished, unlike the successful Langley nozzle, since the roughness criteria ($Re_k <$ 12) did not require it. In addition, there was a 0.001-0.002-inch ($Re_k < 12$) rearward-facing step at the downstream end of the electroform [24]. Here, Re_k is a roughness Reynolds number based on the height of the peak roughness, and the conditions in a smooth-wall boundary layer at the roughness height. However, this step was dramatically reduced by the fall 2002 polishing, which also provided a high-quality finish on the downstream part of the nozzle, without noticeable effect [2].

3.2.2.3 Flaws in the Polish of the Nickel Throat   A small bump can be felt on the nickel bleed lip, and it is possible that this bump is tripping transition. Some small superficial scratches have become visible recently, although the throat remains remarkably clean and free of oil deposits. However, in fall 2002 the polisher believed he could not improve on the throat polish, and the nozzle-wall transition in the nickel throat seems too repeatable and consistent to be due to these small polishing flaws. Although this lip is easily repolished, this process involves risk, so it has been postponed until it seems likely to have an effect.

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3.2.2.4 Vibrations Vibrations of the bleed lip could also introduce disturbances that trip the flow. The tunnel vibrates when the flow starts up, but although these vibrations can clearly be felt, they seem to damp within a second or two. However, the onset of transition seems to occur at the same pressure, regardless of whether this pressure is at the beginning or the end of a run, making this cause seem less likely. The Mach 4 tunnel did not have this problem, but it did not use throat suction either, and the bleed lips may be more sensitive to vibration, particularly in the transverse direction. Measurements of these vibrations are still planned.

3.2.2.5 Upstream Propagation of Noise It also seemed possible that noise might be propagated upstream from the diffuser section, through the boundary layer. The successful Langley design used an open-jet test section, while the Purdue tunnel uses a closed test section. Measurements reported in Ref. [3] showed that the original diffuser centerbody caused separation in the nozzle-wall boundary layer when it began to drop laminar. Measurements in the Langley Mach 6 quiet nozzle showed that transition flashed forward on a flared cone when the nozzle exit shock impinged on the aft end of the cone (Steve Wilkinson, NASA Langley, private communication, 2003). Ref. [25] is the only known publication with data for the effect of an impinging shock on transition in a laminar boundary layer; transition could occur upstream of the nominal shock impingement point, even below Mach 2. Upstream propagation of disturbances remained a concern, even with the new model support design, due to the jets of air from the bleed-slot suction that enter the diffuser downstream. However, when the jets were removed by plumbing this bleed air directly to the vacuum tank, there was no marked effect [4]. In addition, more recent measurements seem to show that downstream noise separates an incoming laminar boundary layer before it causes transition. The extensive measurements reported in Craig Skoch's Ph.D. thesis did not show any effect of the downstream disturbances on transition upstream; in every case separation appeared to occur rather than transition [8, 11].

3.2.2.6 Leaks Leaks in the low-pressure sections can cause air to jet into the nozzle, tripping the boundary layer. Although testing with soap films while the nozzle was under pressure did not show such leaks, small leaks were still a concern. However, more sensitive leak tests were carried out with a helium sniffer, and these failed to show any leaks in the critical portions of the tunnel [5]. During early 2006, small leaks were purposely introduced into the contraction, while the tunnel was running quiet at fairly high Reynolds number. In each case, the leaks did not change the pressure at which the flow dropped quiet, they only served to increase the number of turbulent spikes evident during the mostly-quiet period. These measurements will be reported in Thomas Juliano's M.S. thesis.

3.2.2.7 Wall Temperatures The nozzle-wall temperature distribution decreases much more rapidly downstream than was initially expected. However, computations suggest this effect should be minor, and measurements with modified temperature distributions provide no evidence of a significant effect on transition [1].

3.3 Results Obtained with Surrogate Throat

3.3.1 Introduction

The high probability that bleed-slot unsteadiness has been limiting quiet flow received strong support from measurements using the surrogate throat. An aluminum surrogate throat section was turned on a CNC lathe to a contour nominally identical to the highly polished electroformed section. Fig. 3 shows the primary throat, with a one-piece electroformed interior to 19 inches downstream of the throat. The surrogate replaces this first 30.265 inches of the 102-inch nozzle with aluminum. It differs by lacking a high polish, and by the presence of joints. It was hoped that quiet flow would be obtained under conditions similar to the 8 psia found using the electroformed section, since the high smoothness of the electroform might not be critical at the low pressures where quiet flow was appearing. The surrogate would then provide a test-specimen throat section that could be readily instrumented and otherwise modified, with low risk and cost.
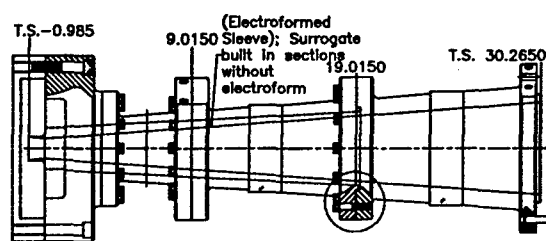

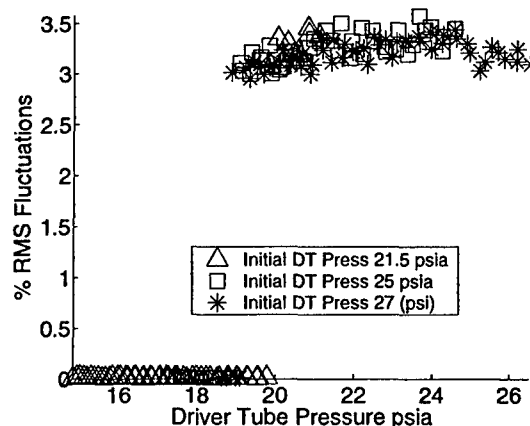Figure 3: Throat section of nozzle (axial station dimensions in inches)

Figure 4: RMS pitot pressure on centerline at $z = 75.3$ in. with *surrogate* throat

3.3.2 Early Measurements with Surrogate Throat

The surrogate throat was first tested in mid-March 2005. Pitot-pressure measurements (Fig. 4) were made on the nozzle centerline near the beginning of the test area at the usual stagnation temperature of $160°C$. *To our surprise, these repeatable measurements showed the flow dropping quiet at 19-20 psia, nearly 2.5 times higher than with the highly polished electroformed throat.* The flow dropped quiet at nearly the same pressure, independent of the time during the run when that pressure occurred. In addition, the fluctuations no longer rose through the intermittent region before falling to quiet levels, the quiet levels appeared to be lower, and the noisy-tunnel levels appeared to be about the same.

Since transition is much delayed using a throat with a lesser surface quality, it appeared that the early 8 psia transition was due to some very small flaw in the bleed-lip contour of the electroformed section. The bleed lips of the nozzle throats were therefore measured in order to

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check the coordinates. Fig. 5 shows the results for the surrogate lip (here, the axial coordinate is zero at the throat, but the sign is reversed from z, and it increases going upstream). The coordinates appear to be nearly exactly as specified. The nickel nozzle was then measured, as shown in Fig. 6. While the coordinates are generally as designed, there is a 0.001-inch kink near the inner shoulder at the 90-deg. azimuth (and also, to a lesser extent, near the 270-deg. azimuth). This kink is the only known feature in which the nickel nozzle is inferior to the surrogate, so it appears to account for the difference in performance.
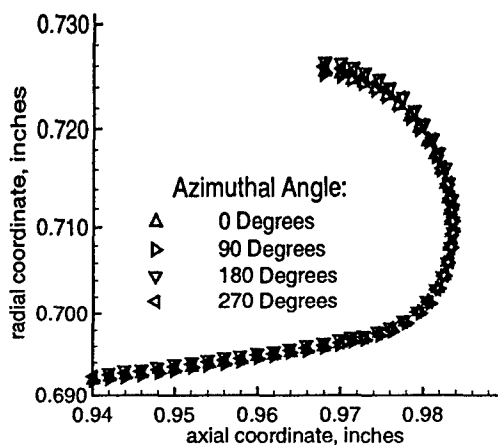

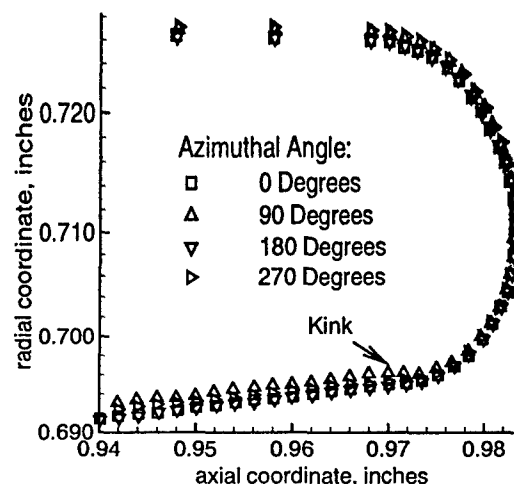Figure 5: Measured Coordinates of Surrogate Lip

Figure 6: Measured Coordinates of Electroformed Lip

This kink aggravates the problem with separation near the lip, and apparently causes the early nozzle-wall transition at 8 psia. The lip of the nickel nozzle had not been measured previously, due to concerns about damaging the 1-microinch-RMS mirror finish. Figs. 3 and 4 of Ref. [24] show measurements obtained by the manufacturer in the throat of the nickel nozzle, but these measurements did not extend to the lip contour. Ref. [24] does show that the electroform distorted about 0.002 inches out of round when it was removed from the mandrel (about 0.1%). Although detailed records no longer exist for the subsequent machining process (private communication, Larry DeMeno, Allied Aerospace, July 2005), it appears that the electroform was aligned in the lathe as though it was axisymmetric, before the tip and upper surface of the bleed lip were machined. The flaw which was then machined into the lip was not detected due to concerns about damaging the surface finish. In hindsight, these concerns were excessive and unwarranted, since a high-quality measurement need not damage the finish anyway.

3.3.3 Recent Experience with Surrogate Throat

More recent experience with the surrogate throat was summarized in Ref. [9]. An 0.002-inch downstream-facing step at the end of the surrogate was removed, increasing the quiet-flow stagnation pressure to 37 psia. An atttempt at repolishing added a nick to the lip, reducing quiet flow to 12 psia. Polishing the nick raised quiet flow to 34 psia. A professional repolishing of the whole surrogate throat then raised the quiet-flow pressure to about 94 psia.

Our experience in early 2006 continues to show the extreme sensitivity of the quiet-flow pressure. At one point, for about two weeks in February, several dozen runs were obtained at a quiet flow pressure of about 120 psia, which was the maximum pressure that the aluminum surrogate throat was rated for. The structural analysis of the throat was revisited, and it was decided to pressure-test it to 270 psia, enabling regular operation at 180 psia. Immediately before the air pressure test, the nozzle ran quiet at 120 psia. Immediately after, it ran quiet only at about 65 psia, perhaps because the high pressure load slightly distorted the lip, or one of the joints, or because some particulate damaged the throat finish, although no additional stratches were noticeable. However, at the end of February, it then ran quiet at 130 psia, as shown in Fig. 7. Here, the run was started at 140 psia, and the driver tube temperature was set to 150°C. The pitot probe was on the centerline at z = 93.4 in. The first part of the run is noisy, and then the pitot-pressure fluctuations drop markedly at about 1.2 sec., after which the flow is quiet, with occasional turbulent spikes. The stagnation pressure is shown in the blue trace, which is measured on the wall, near the entrance to the contraction. It is about 130 psia when the flow drops quiet. The stagnation pressure drops in stairsteps, each time the expansion wave in the driver tube reflects from the entrance to the contraction.
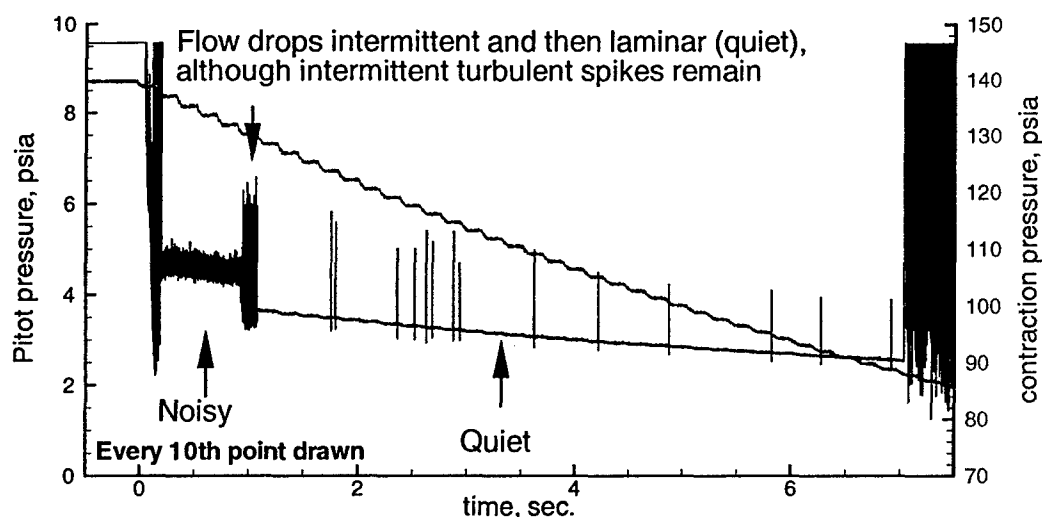

Figure 7: Pitot and contraction-wall pressures showing quiet flow at high Reynolds number

Although this 130 psia quiet flow lasted for most of a week, it then disappeared, and the tunnel was quiet only to about 50 psia. It is now clear the tunnel is capable of running quiet to high Reynolds number. It is also clear that much remains to be done to determine the maximum feasible quiet Reynolds number, and the conditions necessary for reliable quiet flow at this Reynolds number.

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3.4 Future Plans

At present we suspect that a high sensitivity to roughness and the lip shape is the cause of the variability in the quiet-flow pressure. Recall that the Rutgers computations predict that a separation bubble is still present even on the as-designed contour. If the new Rutgers contour is machined into the lip and it successfully eliminates separation, any sensitivity to small changes in surface contour should be reduced.

Since the surrogate throat is sometimes running quiet to high Reynolds number, and the nickel throat has never run quiet above 8 psia, the lip of the nickel throat will first be modified to the new Rutgers shape [10], thereby also removing the small kink evident in Fig. 6. The nickel throat will then be repolished. It seems likely that reliable high Reynolds number quiet flow should then result, as a high-quality surface finish is much easier to maintain on the harder nickel electroform, and the electroform also eliminates the roughness due to the throat-region joints. These improvements to the quiet wind-tunnel performance are being supported under a new AFOSR Grant, FA9550-06-1-0182.

4 Research in Support of STAR

A portion of the STAR effort has assisted in the development and operation of the Mach-6 tunnel. In addition, three other tasks have been supported.

4.1 Reviews of the Existing Experimental Database

A portion of the STAR effort involves a review of the existing experimental literature. This has two purposes: (1) to help identify the mechanisms likely to be important for transition on vehicles of current interest, and (2) to identify test cases useful for developing and validating mechanism-based prediction methods. A portion of this work has been published in Ref. [14]. Related work towards validating a different code was also published [18].

4.2 Towards Validation of the STABL Code

Another portion of the STAR effort made use of the presence of Lt. Tyler Robarge, who was assigned to Purdue to obtain an M.S. degree as a Hertz Fellow. Lt. Robarge learned to use the STABL code being developed at the University of Minnesota for the STAR program. He helped in debugging the code and making it more user friendly, and he did a careful study of the effect of the transport properties on the results, for three test cases [15, 16].

4.3 Measurements of the Mechanisms of Transition on a Blunt Cone at Angle of Attack

The primary experimental effort has been focused on measuring the mechanisms of transition on a blunt cone at angle of attack. Nosetip roughness appears to be the most likely explanation for the onset of windside-forward transition on blunt cones at angle of attack [14]. Since a cone at angle of attack appears to be generic for a gliding reentry vehicle requiring lift, and since transition is most

important on the windward side, where the heating is highest, understanding the mechanisms for windside-forward transition appears to be a critical task in the development of gliding reentry vehicles.

Previous experiments regarding nosetip roughness effects on blunt-cone transition were carried out in more expensive facilities at high Reynolds number; many of these facilities no longer exist, and others are not affordable. The operating range of the Purdue Mach-6 tunnel was extended from a freestream Reynolds number of 3 million per foot to 6 million per foot, as part of an effort to study these effects in an affordable way, even if the freestream noise remains at conventional levels. Although preliminary indications suggest that sufficient Reynolds number can be obtained to be able to study the problem, no conclusive results have been obtained as yet. Measurements of this effect and of the hypersonic crossflow instability are to form Erick Swanson's Ph.D. thesis, which should be completed during 2006-2007.

5   Acknowledgements

6   References

[1] Steven P. Schneider, Shin Matsumura, Shann Rufer, Craig Skoch, and Erick Swanson. Progress in the operation of the Boeing/AFOSR Mach-6 quiet tunnel. Paper 2002-3033, AIAA, June 2002.

[2] Steven P. Schneider, Shin Matsumura, Shann Rufer, Craig Skoch, and Erick Swanson. Hypersonic stability and transition experiments on blunt cones and a generic scramjet forebody. Paper 2003-1130, AIAA, January 2003.

[3] Steven P. Schneider, Craig Skoch, Shann Rufer, and Erick Swanson. Hypersonic transition research in the Boeing/AFOSR Mach-6 quiet tunnel. Paper 2003-3450, AIAA, June 2003.

[4] Steven P. Schneider, Craig Skoch, Shann Rufer, Erick Swanson, and Matt Borg. Bypass transition on the nozzle wall of the Boeing/AFOSR Mach-6 quiet tunnel. Paper 2004-0250, AIAA, January 2004.

[5] Steven P. Schneider, Shann Rufer, Craig Skoch, Erick Swanson, and Matthew P. Borg. Instability and transition in the Mach-6 quiet tunnel. Paper 2004-2247, AIAA, June 2004.

[6] Steven P. Schneider, Craig Skoch, Shann Rufer, Erick Swanson, and Matthew P. Borg. Laminar-turbulent transition research in the Boeing/AFOSR Mach-6 quiet tunnel. Paper 2005-0888, AIAA, January 2005.

[7] Ezgi S. Taskinoglu, Doyle D. Knight, and Steven P. Schneider. A numerical analysis for the bleed slot design of the Purdue Mach-6 wind tunnel. Paper 2005-0901, AIAA, January 2005.

[8] Craig Skoch, Steven P. Schneider, and Matthew P. Borg. Disturbances from shock/boundary-layer interactions affecting upstream hypersonic flow. Paper 2005-4897, AIAA, June 2005.

[9] Matthew P. Borg, Thomas J. Juliano, and Steven P. Schneider. Inlet measurements and quiet-flow improvements in the Boeing/AFOSR Mach-6 quiet tunnel. Paper 2006-1317, AIAA, January 2006.

[10] Selin Aradag, Doyle D. Knight, and Steven P. Schneider. Simulations of the Boeing/AFOSR Mach-6 wind tunnel. Paper 2006-1434, AIAA, January 2006.

[11] Craig R. Skoch. *Disturbances from Shock/Boundary-Layer Interactions Affecting Upstream Hypersonic Flow*. PhD thesis, School of Aeronautics and Astronautics, Purdue University, December 2005. Available from DTIC as ADA441155.

[12] Erick Swanson. Mean flow measurements and cone flow visualization at Mach 6. Master's thesis, School of Aeronautics and Astronautics, Purdue University, December 2002.

[13] Matthew P. Borg. Characteristics of the contraction of the Boeing/AFOSR Mach-6 quiet tunnel. Master's thesis, School of Aeronautics and Astronautics, Purdue University, December 2005. Available from DTIC as ADA441151.

[14] Steven P. Schneider. Hypersonic laminar-turbulent transition on circular cones and scramjet forebodies. *Progress in Aerospace Sciences*, 40(1-2):1–50, 2004.

[15] Tyler Robarge and Steven P. Schneider. Laminar boundary-layer instabilities on hypersonic cones: Computations for benchmark experiments. Paper 2005-5024, AIAA, June 2005.

[16] Tyler Robarge. Laminar boundary-layer instabilities on hypersonic cones: Computations for benchmark experiments. Master's thesis, Purdue University, School of Aeronautics and Astronautics, July 2005. Archived in DTIC as ADA437208.

[17] Shann J. Rufer. *Hot-Wire Measurements of Instability Waves on Sharp and Blunt Cones at Mach 6*. PhD thesis, School of Aeronautics and Astronautics, Purdue University, December 2005.

[18] Ian J. Lyttle, Helen L. Reed, Alexander N. Shiplyuk, Anatoly A. Maslov, Dmitry A. Buntin, Eugene V. Burov, and Steven P. Schneider. Numerical-experimental comparisons of second-mode behavior for blunted cones. *AIAA Journal*, 43(8):1734–1743, August 2005.

[19] R. Benay and B. Chanetz. Design of a boundary layer suction device for a supersonic quiet tunnel by numerical simulation. *Aerospace Science and Technology*, 8:255–271, 2004.

[20] Steven P. Schneider. *Effects of Controlled Three-Dimensional Perturbations on Boundary Layer Transition*. PhD thesis, Graduate Aeronautical Laboratories, California Institute of Technology, Pasadena, California, 1989. DTIC citation AD-A215080.

[21] Laura Pauley, Parviz Moin, and William Reynolds. The instability of two-dimensional laminar separation. In *Low Reynolds Number Aerodynamics*, pages 82–92, Berlin, 1989. Springer-Verlag.

[22] P. Klebanoff and K. Tidstrom. Two-dimensional roughness element induces boundary-layer transition. *Physics of Fluids*, 15(7):1173–1188, 1972.

[23] I.E. Beckwith, F.J. Chen, and T.R. Creel. Design requirements for the NASA Langley supersonic low-disturbance wind tunnel. Paper 86-0763, AIAA, 1986.

[24] Steven P. Schneider and Craig Skoch. Mean flow and noise measurements in the Purdue Mach-6 quiet-flow Ludwieg tube. Paper 2001-2778, AIAA, June 2001.

[25] J.C. Leballeur and Jean Delery. Experimental investigation into the effect of shock wave reflection on boundary layer transition. *La Recherche Aerospatiale, English Edition*, 1974-3:117–136, May-June 1974. NASA citation 76N10992.